HIGH-ENERGY SOLAR FLARE OBSERVATIONS BY YOHKOH: A REVIEW

T. Kosugi

National Astronomical Observatory, Mitaka, Tokyo 181, Japan

Abstract

Hard X-ray and γ-ray observations of solar flares by the *Yohkoh* satellite are reviewed. A special attention is paid for hard X-ray imaging with the Hard X-ray Telescope (HXT), which has provided us with new information on where and how energetic electrons are accelerated, transported, and lose their energy in the flaring magnetic loop structure. It has been revealed that several different types of hard X-ray sources coexist in a flare. They are "(double) footpoint source(s)", "loop-top impulsive source", "loop-top gradual source", "remote-site impulsive source", "super-hot thermal source", and so on, each of which may represent a different aspect of flare energetics. General characteristics of these types of sources are summarized and their interrelation and implication discussed.

1. Introduction

The *Yohkoh* satellite (Ogawara *et al.* 1991) carries two types of instruments which are dedicated for the study of high-energy aspects of solar flares. One is the Hard X-ray Telescope (HXT; Kosugi *et al.* 1991) and the other is the hard X-ray and γ-ray spectrometers (HXS and GRS), two constituents of the Wide-Band Spectrometer (WBS; Yoshimori *et al.* 1991). The HXT is a hard X-ray imager of a Fourier-synthesis type with 64 elements and has the following advantages over its predecessors: (i) simultaneous imaging in four energy bands, namely, the L-band (13.9–22.7 keV), M1-band (22.7–32.7 keV), M2-band (32.7–52.7 keV), and H-band (52.7–92.8 keV); (ii) angular resolution as high as $\sim$ 5 arcsec with a wide field of view covering the whole Sun; (iii) basic temporal resolution of 0.5 s; and (iv) high sensitivity with a total geometrical aperture of $\sim$ 60 cm^2. Advantages of the HXS and GRS spectrometers are: (i) 32-channel pulse-height analysis in the hard X-ray range (20–600 keV), enabling us to precisely measure the spectral shape; and (ii) high sensitivity for detecting γ-rays above $\sim$ 10 MeV. One more important advantage of us is that we have the Soft X-ray Telescope (SXT; Tsuneta *et al.* 1991) on board the same satellite; SXT is especially complementary to HXT for flare studies in that it reveals the magnetic loop structure of a flaring region in which particle acceleration, one of the main objectives of HXT, takes place. Combined together, these instruments provide us with fruitful observations which are relevant for revealing the site(s) and mechanism(s) of magnetic energy release, particle acceleration, and energy transport in solar flares.

Since the start of routine observations in October, 1991, these instruments have been operating well. For example, HXT has so far detected more than 800 flares (as of August 1993), out of which more than two thirds are intense enough for us to synthesize images, including about a dozen X-class and $\sim$ 200 M-class events. The performance of HXT in orbit and some initial results are briefly discussed in a series of letter papers (Kosugi *et al.* 1992; Sakao *et al.* 1992; Matsushita *et al.* 1992) which appeared in *'Initial Results from Yohkoh'* (a special feature of ***Publ. Astron. Soc. Japan***, Vol. **44**, No. 5). The same feature includes papers describing initial results from HXS and GRS (Yoshimori *et al.* 1992a,b). For subsequent works, see the proceedings of the *Yohkoh* International Symposium held at Sagamihara on 23 - 25 February, 1993 (Uchida *et al.* 1994) and papers cited therein, as well as contribution papers in these proceedings. As far as γ-ray observations are concerned, the Sun has not been so cooperative with us except for the initial three months just after the *Yohkoh* launch; no γ-ray flares have been detected since January, 1992. Results from GRS have been concisely summarized by Yoshimori *et al.* (1994). Thus in this review, we will concentrate our attention upon hard X-ray observations, especially imaging with HXT.

2. A Preliminary Summary of HXT Observations

Several interesting characteristics of hard X-ray sources revealed with HXT during the initial period (October, 1991 – March, 1992) have been summarized as follows (Kosugi *et al.* 1992; Kosugi 1993):

- Hard X-ray flares observed in the HXT L-band (13.9 - 22.7 keV) usually show one or more long, thin structures which seem to trace magnetic loops. In fact hard X-ray images generally resemble the corresponding soft X-ray images taken with SXT. Maybe emission from a high-temperature ($T \sim 20$ MK) plasma filling the loop(s) contributes to some extent to the hard X-ray emission detected in the L-band.

- In higher-energy (M1-, M2-, and H-band) images, hard X-ray sources become more compact and patchy. Typically two separate sources are observed at the two ends of the long, thin structure seen in the L-band, suggesting that energetic electrons, possibly accelerated near the loop top, propagate along the magnetic loop and stream down into the lower atmosphere at their footpoints, where they collide the thick target and emit hard X-rays via electron–ion Bremsstrahlung.

- Correspondingly the average height of hard X-ray sources decreases with increasing photon energies (Matsushita *et al.* 1992).

- Sometimes a sudden shift of hard X-ray source is observed from one location to another during impulsive peaks, suggestive of successive flaring of adjacent loops.

Although these statements hold for the majority of impulsive flares observed with HXT, subsequent observations have not only supplemented the contents by many details but also added some other important new results. In the following, we will try to include as latest results as possible and organize our results from a viewpoint of classification of hard X-ray sources in solar flares.

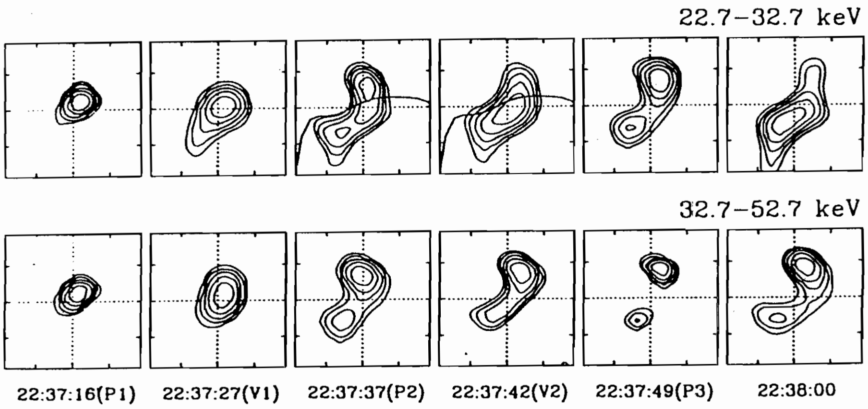

Fig. 1. Hard X-ray images of the 15 November, 1991 flare. M1-band (22.7–32.7 keV; top) and M2-band (32.7–52.7 keV) images are given at the peaks (P1, P2, and P3) and the valleys (V1 and V2) of spikes during the impulsive phase. The solar north is to the top, west to the right. Each map covers 37 × 37 arcsec. The magnetic neutral line is shown in the M1-band images at P2 and V2. Contour levels are 18, 25, 35, 50, and 71 % of the maximum brightness for each map (after Sakao *et al.* 1992).

3. Classification of Hard X-ray Sources: A Trial

3.1. Double-Footpoint Sources in the Impulsive Phase

Even in the era of the first hard X-ray imaging experiments made by *SMM* and *Hinotori* more than a decade ago, it was recognized that some impulsive flares are characterized by the double-source structure, and it was claimed that this is evidence for nonthermal electron precipitation towards the two ends of a single flaring loop (e.g. Hoyng *et al.* 1981; Duijveman *et al.* 1982). Although this conclusion may be correct as shown below, there was no firm observational base which unambiguously supports this interpretation; the X-ray energy range was below $\sim$ 20 keV where contamination from thermal emission is not negligible, and also the temporal resolution was not sufficient as to confirm the expected simultaneity between the two sources (e.g. MacKinnon *et al.* 1985).

The HXT observations have proved that the double-source structure is one of the fundamental characteristics of impulsive flares. Sakao *et al.* (1992) have revealed, in the case of the X-class flare of 15 November, 1991, that two sources are located at both sides of a magnetic neutral line (figure 1). The double-source structure is most pronounced at X-ray energies $\gtrsim$ 30 keV at the times of individual peaks, whereas hard X-rays at $\lesssim$ 30 keV at the valleys between the peaks originate from near the apex of the flaring loop. This may be interpreted by the DC electric field–runaway acceleration model (Benka and Holman 1992), in which electron acceleration takes place together with direct heating. Here we suggest such a process working near the loop top, with enhanced acceleration at the peaks. Or this may be explained by the trap-plus-precipitation model (Melrose and Brown 1976) with a strong scattering process operating. Again we imply here electron trapping near the loop apex. It is noteworthy that the white-light flare brightenings (Hudson *et al.* 1992), which were coincident with the hard X-ray double sources (Sakao *et al.* 1992), strongly support the electron-precipitation interpretation. In this event, a systematic increase of the separation between the double sources was also found together with a systematic increase of the angle sustained by the line connecting the double sources and the magnetic neutral line, suggestive of a multiple loop system flaring successively

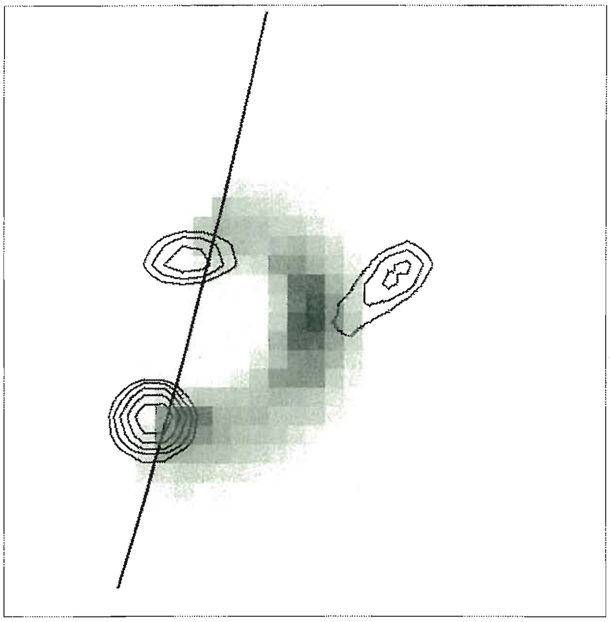

Fig. 2. Hard X-ray (M2-band; 32.7–52.7 keV; in contours) *versus* soft X-ray (Be filter; in grey scale) images of the 13 January, flare that occurred near the west solar limb (denoted by solid line). The solar north is to the top, west to the right. The field of view of the map covers 78 × 78 arcsec. Contour levels are 18, 25, 35, 50, and 71 % of the maximum brightness. Accuracy of overlay is estimated to be within ~ 1% arcsec. For more details, see Masuda (1994a) and Masuda *et al.* (1994b).

from strongly sheared loops to less sheared ones with rising energy release site (Sakao *et al.* 1994a; Sakao 1994).

Subsequent analyses of a few dozens of impulsive flares by Sakao (1994; see also Sakao *et al.* 1994b) have confirmed (i) that the double-source structure, in which the two sources are located at both sides of the magnetic neutral line with separations between them ranging from ~ 10 to ~ 30 arcsec, can be found in ~ 40 % of the events examined, (ii) that double sources almost simultaneously vary in intensity with time lags less than a fraction of a second, (iii) that the brighter source tends to correspond to a footpoint where the photospheric magnetic field is the weaker (irrespective of the sense of the magnetic field), and (iv) that the brighter source tends to show a harder hard X-ray spectrum than the other source. These findings, together with results from the above-mentioned case study of the 15 November, 1991 flare, strongly suggest that electrons are accelerated near the apex of a loop or a system of loops, that the electrons precipitate towards the two footpoints with preference towards the weaker magnetic field footpoint, and that individual accelerations take place in different loops. These are important findings to pose a strong constraint upon the acceleration mechanism.

3.2. Loop-Top Sources in the Impulsive Phase

In the impulsive phase of several flares occurring near the solar limb, one more source, in addition to the dominant double footpoint sources discussed in the previous subsection, has been found in the energy range above ~ 20 keV at an altitude of more than 10^4 km above the photosphere (Masuda 1994a,b; Masuda *et al.* 1994b). Surprisingly, at least in some cases, the source is located well above the apex of the corresponding soft X-ray loop (figure 2). Although this hard X-ray source is weak in comparison with the double footpoint sources by about an order of magnitude, it varies its intensity similarly to the footpoint sources, *i.e.*, impulsively. It shows a relatively hard spectrum; if the emission is assumed to be of thermal origin, we get the temperature $T \sim 200$ MK and the emission measure $EM \sim 10^{44} - 10^{45}$ cm^{-3}. Hence there is no doubt that the source is of an impulsive nature.

The existence of an impulsive hard X-ray source above the soft X-ray flaring loop is of crucial importance. First, it informs us that *something* energetic is going on *outside* the bright soft X-ray loop. Second, this *something* is directly related to particle acceleration; it is most likely that we observe the particle acceleration site as the loop-top impulsive source. Finally, the soft and hard X-ray images combined together lead us to speculate the magnetic field topology with a current sheet in which magnetic reconnection is under progress. Thus it is suggested that this source represents the site where the downward plasma outflow, ejected from a reconnection point above the hard X-ray source, collides with an underlying closed magnetic loop and forms a shock. Maybe electrons are energized in the shock (cusp-shaped reconnection hypothesis: see Masuda 1994a; Masuda *et al.* 1994b).

The above result has been obtained from an analysis of ten near-the-limb flares. No clear loop-top impulsive sources have yet been found for flares occurring near the disk center. In this regard, however, it is noteworthy that Takakura *et al.* (1993) found (i) that the hard X-ray brightening seems to start at the top of a single coronal loop, and (ii) that the X-ray source spreads during the rise phase in both directions along the loop, resulting in the double-source structure. If this is the general case, the loop-top impulsive source may appear a little earlier than the double footpoint sources.

3.3. Loop-Top Sources in the Gradual Phase

We see in most of impulsive flares that the HXT L-band (13.0–22.7 keV) time history is dominated by a gradually-varying component upon which impulsive spikes are superposed. In images this gradually-varying source (seen in the L-band) is usually located in between the double footpoint sources (seen in the higher-energy bands). Sometimes it seems that this source fills a large portion of a loop, hence resembling the corresponding soft X-ray sources. This type of sources becomes pronounced as time goes on after the impulsive phase ceases, and is characterized by a very steep hard X-ray spectrum which is typical for thermal emission from a plasma with temperatures ranging from 20 to 40 MK and emission measures from 10^{46} to 10^{49} cm^{-3} (Masuda 1994a,b).

Then a question arises how this thermal plasma is created, i.e., whether it is due to direct heating from magnetic energy release or due to evaporated material rising up from the chromosphere, and if the latter is the case, whether the energy is supplied by nonthermal electrons or by heat conduction. These problems are now challenged by several authors (Culhane *et al.* 1994; Inda-Koide *et al.* 1994; Wülser *et al.* 1994) using HXT and SXT data together as well as the Bragg Crystal Spectrometer (BCS) data showing upward motion (blueshifted line emission). The result is still controversial or case by case.

3.4. Remote-Site Impulsive Sources

In some impulsive flares we observe a hard X-ray ($\gtrsim$25 keV) patch appearing at a site remote from the brightest flaring loop seen in HXT L- band (13.9–22.7 keV) or soft X-ray images. One of such cases is the 24 October, 1991 flare (Masuda *et al.* 1994a), in which a compact source appears at the second spike at a site some 40 arcsec south-west of the main flaring region. The site is a unipolar region whose magnetic polarity is the same as that of the western part of the double footpoint sources. Thus Masuda *et al.* concluded that at least two loops are involved at this spike; the outer loop more efficiently accelerates electrons which stream into the remote-site source and emit spiky hard X-rays with a hard spectrum, while the inner loop mainly produces a high-temperature plasma which reveals itself as a gradual source with a softer spectrum. The interaction of the two loops may explain the coincident brightenings of the two sources. Since this loop-loop interaction scenario seems to be in contradiction with the cusp-shaped reconnection hypothesis raised in subsection 3.2, we need further studies.

A similar hard X-ray event is reported by Yaji *et al.* (1994). Further observational evidence for loop-loop interaction has been recently presented by Shimizu *et al.* (1994), Hanaoka (1994), and Inda-Koide (1994).

3.5. Super-Hot Thermal Sources (Type A Flares)

So far we have discussed hard X-ray components that appear in normal impulsive flares. In this and the next subsections, we discuss other components that appear only rarely.

Super-hot thermal flares or type A flares are those characterized by predominance of thermal emission from a $T \gtrsim 30$-MK plasma in the hard X-ray emission (Tanaka *et al.* 1982; Tsuneta *et al.* 1984a). In other words, they are less efficient in particle acceleration. Hence imaging of such flares may provide information on where the primary energy release site of flares is located, how the super-hot thermal plasma is created, and what controls the efficiency of particle acceleration. Also it provides a hint on the origin of loop-top gradual hard X-ray sources (subsection 3.3).

The flare of 6 February, 1992 at 03:10 UT is a nice example to study these points. The flare occurred near the west limb, suitable for measuring the source height. It was composed of two loops which successively flared up (Kosugi et al. 1994). The southern loop, first seen, was a normal flaring loop; its hard X-rays lasted for less than a few minutes, originated mainly from the two footpoints, and showed a power-law spectrum. On the contrary, the northern loop, flaring up some 10 min later, showed typical super-hot thermal flare characteristics: a gradual broad peak lasting for longer than 10 min, a thermal hard X-ray spectrum with temperatures exceeding 30 MK, and lack of associated microwave burst. In this loop the hard X-ray source first appeared near the loop top and then gradually expanded downwards, maybe due to direct heating as a result of primary energy release. At the same time a soft X-ray source, representing $\sim$ 10-MK plasma, brightened first at one of the two footpoints and gradually expanded upwards, maybe tracing the chromospheric evaporation process due to heat conduction from the super- hot plasma. Thus in this northern loop no efficient particle acceleration took place; it seems that the ambient plasma density in the flaring loops caused the different behaviors between the northern and southern loops.

3.6. Gradual Hard Sources (Type C Flares)

This type of flares is characterized by high altitude ($h \sim 5 \times 10^4$ km) hard X-ray sources, gradually varying X-ray and microwave fluxes, X- ray spectral hardening with time, and a relatively large microwave/hard X-ray flux ratio, all of which are suggestive of trapped nonthermal electrons and/or continuous acceleration (Tanaka 1983; Tsuneta *et al.* 1984b; Dennis 1985; Kosugi *et al.* 1988). No comprehensive studies on this type of flares have yet been made from *Yohkoh* HXT data. Although no typical intense type C flares like that of 13 May, 1981 (Tsuneta *et al.* 1984b) have been observed by *Yohkoh*, we have several examples that show some properties of type C. Case studies of them are highly desirable and will be made in near future.

4. Final Remarks

As more than two years have elapsed since the launch of *Yohkoh*, many works have been done in the field of high-energy solar flare studies. It has become clear that, even in the hard X-ray range, solar flares exhibit several different types of sources, i.e., "(double) footpoint source(s)", "loop-top impulsive source", "loop-top gradual source", "remote-site impulsive source", "super-hot thermal source", and so on. Different characteristics of the individual types of sources have been given, and it is suggested that each of them may represent a different aspect of flare energetics.

In this review, the author has made efforts as far as possible in clarifying what has been confirmed and what has not. In order to reach our goal, we still have many works to be done.

Acknowledgements: The author wishes to express his thanks to his colleagues in the HXT experiment. The *Yohkoh* project is a team effort, including not only Japanese but also many U.S. and U.K. colleagues. ISAS, NASA, and SERC have been continuously supporting the *Yohkoh* operation.

References

1. Benka, S. and Holman, G.D., 1992, *Astrophys. J.* **391**, 854.
2. Culhane, J.L., Phillips, A.T., Inda-Koide, M., Kosugi, T., Fludra, A., Kurokawa, H., Makishima, K., Pike, C.D., Sakao, T., Sakurai, T., Doschek, G., and Bentley, R.D., 1994, *Solar Phys.*, in press.
3. Dennis, B. R., 1985, *Solar Phys.* bf 100, 465.
4. Duijveman, A., Hoyng, P., and Machado, M.E., 1982, *Solar Phys.* **81**, 137.
5. Hanaoka, Y., 1994, *Astrophys. J. (Letters)* **420**, L37.
6. Hoyng, P., Machado, M.E., Duijveman, A., Boelee, A., de Jager, C., Fryer, R., Galama, M., Hoekstra, R., Imhof, J., Lafleur, H., Maseland, H.V.A.M., Mels, W.A., Schadee, A., Schrijver, J., Simnett, G.M., Svestka, Z., van Beek, H.F., van Tend, W., van der Laan, J.J.M., van Rens, P., Werkhoven, F., Willmore, A.P., Wilson, J.W.G., and Zandee, W., 1981, *Astrophys. J. Lett.* **244**, L153.
7. Hudson, H.S., Acton, L.W., Hirayama, T., and Uchida, Y., 1992, *Publ. Astron. Soc. Japan* **44**, L77.
8. Inda-Koide, M., 1994, in these proceedings.
9. Inda-Koide, M., Makishima, K., Kosugi, T., Sakao, T., 1994a, in Y. Uchida *et al.* (eds.), *'X-ray Solar Physics from Yohkoh'* (Universal Academy Press: Tokyo), pp.99–103.
10. Kosugi, T., 1993, in J. Linsky and S. Serio (eds.), *'Physics of Solar and Stellar Coronae'* (Kluwer Academic Publ.), pp.131–138.
11. Kosugi, T., Dennis, B. R., and Kai, K., 1988, *Astrophys. J.* **324**, 1118.
12. Kosugi, T., Makishima, K., Murakami, T., Sakao, T., Dotani, T., Inda, M., Kai, K., Masuda, S., Nakajima, H., Ogawara, Y., Sawa, M., and Shibasaki, K., 1991, *Solar Phys.* **136**, 17.
13. Kosugi, T., Sakao, T., Masuda, S., Makishima, K., Inda, M., Murakami, T., Ogawara, Y., Yaji, K., and Matsushita, K., 1992, *Publ. Astron. Soc. Japan* **44**, L45.
14. Kosugi, T., Sakao, T., Masuda, S., Hara, H., Shimizu, T., Hudson, H.S., 1994, in these proceedings.
15. MacKinnon, A.L., Brown, J.C., and Hayward, J., 1985, *Solar Phys.* **99**, 231.
16. Masuda, S., 1994a, Ph.D. thesis (University of Tokyo).
17. Masuda, S., 1994b, in these proceedings.
18. Masuda, S., Kosugi, T., and Sakao, T., 1994a, in Y. Uchida *et al.* (eds.), *'X-ray Solar Physics from Yohkoh'* (Universal Academy Press: Tokyo), pp.123–126.
19. Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., and Ogawara, Y., 1994b, *Nature*, submitted.
20. Matsushita, K., Masuda, S., Kosugi, T., Inda, M., and Yaji, K., *Publ. Astron. Soc. Japan* **44**, L89.
21. Melrose D.B., and Brown, J.C, 1976, *Monthly Notices Roy. Astron. Soc.* **176**, 15.
22. Ogawara, Y., Takano, T., Kato, T., Kosugi, T., Tsuneta, S., Watanabe, T., Kondo, T., and Uchida, Y., 1991, *Solar Phys.* **136**, 1.
23. Sakao, T., 1994, Ph.D. thesis (University of Tokyo).

24. Sakao, T., Kosugi, T., Masuda, S., Inda, M., Makishima, K., Canfield, R. C., Hudson, H. S., Metcalf, T. R., Wuelser, J.-P., Acton, L. W., and Ogawara, Y., 1992, *Publ. Astron. Soc. Japan* **44**, L83.
25. Sakao, T., Kosugi, T., Masuda, S., Yaji, K., Inda-Koide, M., and Makishima, K., 1994a, in Y. Uchida *et al.* (eds.), *'X-ray Solar Physics from Yohkoh'* (Universal Academy Press: Tokyo), pp.91–94.
26. Sakao, T., Kosugi, T., Masuda, S., Yaji, K., Inda-Koide, M., and Makishima, K., 1994b, in these proceedings.
27. Shimizu, T., Tsuneta, S., Acton, L. W., Lemen, J. R., Ogawara, Y., and Uchida, Y., 1994, *Astrophys. J.* **422**, 906.
28. Takakura, T., Inda, M., Makishima, K., Kosugi, T., Sakao, T., Masuda, S., Sakurai, T., and Ogawara, Y., 1993, *Publ. Astron. Soc. Japan* **45**, 737.
29. Tanaka, K., 1983, in P. B. Byrne and M. Rodono (eds.), *'Activity in Red-Dwarf Stars'*, IAU Colloq. **71**, 307.
30. Tanaka, K., Watanabe, T., Nishi, K., and Akita, K., 1982, *Astrophys. J. Lett.* **254**, L59.
31. Tsuneta, S., Nitta, N., Ohki, K., Takakura, T., Tanaka, K., Makishima, K., Murakami, T., Oda, M., and Ogawara, Y., 1984a, *Astrophys. J.* **284**, 827.
32. Tsuneta, S., Takakura, T., Nitta, N., Ohki, K., Tanaka, K., Makishima, K., Murakami, T., Oda, M., Ogawara, Y., and Kondo, I., 1984b, *Astrophys. J.* **280**, 887.
33. Tsuneta, S., Acton, L., Bruner, M., Lemen, J., Brown, W., Caravalho, R., Catura, R., Freeland, B., Jurcevich, B., Morrison, M., Ogawara, Y., Hirayama, T., and Owens, J., 1991, *Solar Phys.* **136**, 37.
34. Uchida, Y., Watanabe, T., Shibata, K., and Hudson, H. S. (eds.), 1994, *'X-ray Solar Physics from Yohkoh'* (Universal Academy Press: Tokyo).
35. Wülser, J.-P., Canfield, R.C., Acton, W.A., Culhane, J. L., Phillips, A., Fludra, A., Sakao, T., Masuda, S., Kosugi, T., and Tsuneta, S., 1994, *Astrophys. J.* **424**, 459.
36. Yaji, K., Kosugi, T., Sakao, T., Masuda, S., Inda-Koide, M., and Hanaoka, Y., 1994, in these proceedings.
37. Yoshimori, M., Okudaira, K., Hirasima, Y., Igarashi, T., Akasaka, M., Takai, Y., Morimoto, K., Watanabe, T., Ohki, K., Nishimura, J., Yamagami, T., Ogawara, Y., and Kondo, I., 1991, *Solar Phys.* **136**, 69.
38. Yoshimori, M., Takai, Y., Morimoto, K., Suga, K., Ohki, K., Watanabe, T., Yamagami, T., Kondo, I., and Nishimura, J., 1992a, *Publ. Astron. Soc. Japan* **44**, L51.
39. Yoshimori, M., Takai, Y., Morimoto, K., Suga, K., and Ohki, K., 1992b, *Publ. Astron. Soc. Japan* **44**, L107.
40. Yoshimori, M., Suga, K., Morimoto, K., Hiraoka, T., Sato, J., Kawabata, K., and Ohki, K., 1994, *Astrophys. J. Suppl.* **90**, 639.